Brass Tacks

An in-depth look at a radio-related topic

Intermodulation distortion

One day I was in Bountiful (north of Salt Lake City) visiting a friend of mine, and happened to have brought along a mobile radio I was using as a portable, a Kenwood TM-241A. After leaving my friend, I thought it would be a good time to play radio, and see what repeaters I could hit. I had the radio set to the Mt. Ogden repeater, at 146.900 MHz, and was listening while I pulled out my pen and a pad to take notes.

Out of nowhere, I heard the voice of Gordon Smith K7HFV in the mobile's speaker, but only for a couple of seconds. And his voice didn't sound normal, but was accompanied by strange cyclic tones and beeps. So, I called out to Gordon on that frequency, but he didn't respond. Then, I heard the slightly distorted voice of Dennis Nelson N7FOD, and it became obvious that these two were talking with each other. So, I called out to Dennis this time, but still no response.

Going on a hunch, I tuned to the UARC repeater at 146.620, and there the two were, talking up a storm. I cut in again, but this time they both acknowledged me. Suddenly, I realized I had been hearing what's known as ***intermodulation distortion*** ("IMD" or "intermod" for short) on the Mt. Ogden repeater frequency. Right away, I started jotting down numbers, to find the mystery frequency (X) that is missing from the intermod equation, since the conversation taking place on frequency Y (146.620), was being heard by me on frequency Z (146.900):

$$2X - Y = Z$$

$$2X - 146.620 = 146.900$$

$X = 146.760$, the "76" repeater

This meant that, while Gordon and Dennis were talking on the UARC repeater, somebody probably keyed up on the 76 repeater, throwing the 76 carrier, along with Gordon and Dennis' conversation, into my mobile, allowing me to momentarily hear it all, on the Mt. Ogden repeater frequency. It's important to note that the Mt. Ogden repeater didn't experience any of this action, because ***it was all taking place in my mobile radio***. So, what's going on here?

The phenomenon

Amateur radio receivers have what's known as the ***front end***, the circuit the antenna sends its signals to. Among some filtering and other features, the receiver front end contains two subcircuits of concern, the ***amplifier*** and the ***mixer***. The amplifier is necessary to boost the weak signal arriving from the antenna, into something that conventional circuitry can work with. The mixer converts the amplified signal into one of much lower frequency, using a very stable and specific sine wave generated by the IF (intermediate frequency) oscillator.

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A *linear* circuit is one in which the output voltage is proportional to the input voltage. The purpose of a linear amplifier is to output a waveform that's identical to its input waveform, only with increased intensity. Unfortunately, most amplifiers are not perfect, and will exhibit some ***nonlinearity***; that is, in some conditions, its output waveform will not be perfectly proportional to its input waveform. Furthermore, mixer circuits are nonlinear by design.

As a signal encounters one of these circuit nonlinearities, reduced-power integer multiples of its frequency, known as ***harmonics***, appear at the output. Most of the harmonics do not significantly impact the output signal, because their voltage levels decrease as their frequencies increase. Moreover, single-frequency harmonics can often be removed by simple filter circuitry.

When a signal of a second frequency is introduced to the circuit nonlinearities, however, a new set of circumstances emerge, in which the output signals become compounded by the presence of two sets of harmonics, which are a little more difficult to manage. These two new signals can combine in ways that produce ***distortion*** to the listener, and that combination, which is known as a ***product***, is the subject of this discussion.

IMD product order

A single-frequency (known as the *fundamental*) signal will have harmonics at twice its fundamental (second harmonic), three times its fundamental (third harmonic), and so forth. Let's symbolize the two applied fundamental frequencies as f_1 and f_2, whatever they might be. This means that the fundamentals have second harmonics ($2f_1$ and $2f_2$), third harmonics ($3f_1$ and $3f_2$), fourth harmonics ($4f_1$ and $4f_2$), and so on. The prefixed numerals "2" and "3" and "4" (and implied "1") are called the *multipliers* (technically, *coefficients*) of the harmonics.

By the way, if you'd like to try a fun little experiment, to demonstrate the presence of a third harmonic, for example, tune one HT (handheld transceiver) to the 146.760– MHz repeater, and another to 438.480 MHz. Place the two HTs at some distance (say, one or two hundred feet) away from each other, and ask a friend to listen on the HT tuned to 438.480 MHz, while you try and hit the 146.760 repeater with the other HT. You'll find that your friend can hear you quite clearly, because you're actually transmitting on 146.760 MHz – 0.600 MHz = 146.160 MHz, and your friend is listening on 146.160 MHz x 3 = 438.480 MHz, or in other words, the third harmonic of 146.160 MHz.

Intermodulation products appear when integer multiples of these two frequencies, including the fundamentals, combine (add or subtract), such that each product f_P can be calculated as

$$f_P = f_1 + f_2 \qquad\qquad f_P = f_1 - f_2$$

and the ***product order*** is the *sum of absolute values of integer multipliers* of all harmonics.

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Therefore, in each of the above equations, f_P has order |1| + |1| = 2, making f_P in those cases *second-order intermodulation products*. For example, say you have two nearby FM broadcast stations, one at 89.5 MHz, and the other at 103.7 MHz. The resulting second-order intermodulation products will therefore be 103.7 MHz + 89.5 MHz = 193.2 MHz, and 103.7 MHz – 89.5 MHz = 14.2 MHz. Neither of these intermod products will interfere with your broadcast radio, because the two frequencies fall outside that band. Your 20-meter HF radio, however, might pick up the 14.2 MHz product as *noise*, since it does fall within *that* band.

Now, consider higher-order intermod products of the two signals:

$f_P = 2f_2 + f_1$	$f_P = 2f_2 - f_1$	$f_P = 2f_1 + 2f_2$	$f_P = f_1 + 3f_2$
$f_P = 2f_1 + f_2$	$f_P = 2f_1 - f_2$	$f_P = 2f_1 - 2f_2$	$f_P = 2f_1 + 3f_2$

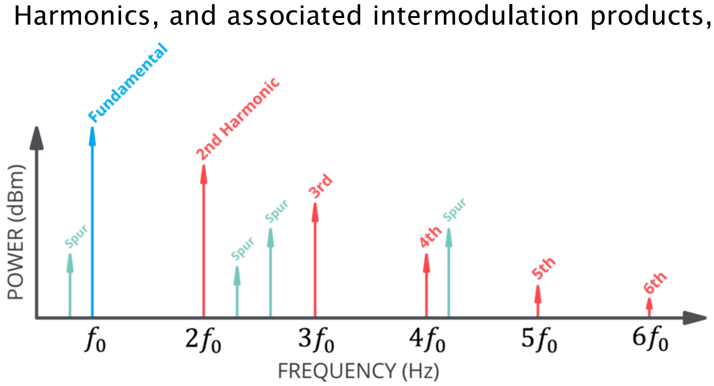
In each equation of the first two columns, f_P has order |2| + |1| = 3, therefore resulting in a *third-order intermodulation product*. In each equation of the third column, f_P has order |2| + |2| = 4, making each a fourth-order product. As you can see, the remaining two equations in the fourth column result in f_P of orders |1| + |3| = 4 and |2| + |3| = 5, respectively.

Consequence of order

If you examine second-order intermod products, you might notice that they tend *not to* fall in the same band as the two original signals. Using the two repeater output frequencies mentioned in the introduction, we have $f_1 + f_2$ = 146.760 MHz + 146.620 MHz = 293.380 MHz, which is far out of our band. (I used the repeater *outputs* because their signals to the repeater inputs, 146.160 MHz and 146.020 MHz, would have been attenuated too much to reach my mobile radio to produce any noticeable audio.) And so it goes, that ***most even-order intermod products likely fall outside the band***, where it will not likely interfere with our receiver.

If you examine third-order intermod products, you might notice that they will often fall in the same band as the original signals. This is why, at $2f_1 - f_2$ = 2 x (146.760 MHz) – 146.620 MHz = 146.900 MHz, the product lies right in the 2-meter band, where it'll interfere with anything you might hear from the 146.900– MHz Mt. Ogden repeater. In the same way, ***most odd-order intermod products will likely fall within the band***, and interfere with our receiver.

Harmonics, and associated intermodulation products, can be represented by *Taylor Series* calculations, which I will spare you from staring at. One result to note, however, is that each harmonic (represented by each Taylor polynomial term), is reduced in intensity from the previous-order harmonic, as can be seen from this graph on the left. This means that, even if a fifth-order intermod product can interfere with our receiver, the interference will likely be imperceptible.



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The result of all this examination is that our concern surrounding intermod is fairly confined to the third-order products. But, even if the fifth-order products are large enough to cause receiver interference, another positive result of the Taylor Series calculation is the fact that, for every dB (about 20%) that you attenuate the fundamental signals, the third-order intermodulation products will actually attenuate 3 dB, or about 50%.

Causes of intermod

As previously mentioned, one source of undesirable intermodulation distortion is the nonlinearities exhibited by the amplifier and the mixer. Because these occur within the circuitry of our receiver, we sometimes refer to it as ***internal IMD*** or *active intermodulation*. But, arising from sources outside your radio, ***external IMD*** or *passive intermodulation (PIM)* can be generated by metallic objects and passive components that pick up radio signals, accidentally mix them by means of a nonlinear component, and broadcast the IMD products. Hams once referred to PIM as the *rusty bolt effect*, seeing how two corroded metals coming in contact with each other can form a crude diode mixer. As a result, IMD was often blamed on oxidized fences and downspouts, although they were rarely the actual cause.

One primary cause of intermodulation distortion is wide-band receiver design, coupled with poor filtering. For example, the American 2-meter band extends from 144.000 MHz to 148.000 MHz. If a receiver is designed to accept only this 4 MHz bandwidth, it's much less likely to fall victim to IMD than one whose input bandwidth extends far enough outside to accept public safety, weather, and commercial traffic, as well as amateur signals. As a result, engineers have incorporated ***bandpass filters*** in many of today's receivers to allow the reception of only a small sub-band, while attenuating all other signals, reducing the opportunity for IMD.

Another cause of IMD in today's HTs is increased receiver sensitivity, some of it brought on by the demand of rubber duck usage. A Yagi antenna can help reduce IMD on HF by attenuating the reception of signals outside its beamwidth. Also, many hams blame odd sounds from their radios on IMD, when in fact they might be hearing front-end overload, poor image rejection, or harmonic distortion. Finally, we tend to think of IMD as a receiver problem, but it can occur in transmitters too.

Summary

Intermodulation distortion is an undesired result of two signals with different frequencies, that encounter a nonlinear circuit. Odd-order, especially third-order, IMD products are the most problematic. It's not as common today as in past years, but an issue that still needs to be addressed in radio receiver design. Often, bandpass filtering or limiting receiver spectrum bandwidth is sufficient for reducing the effects of IMD.

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